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TORONTO CECIL TS - GIS/CABLE INTERFACE ARRESTERS POWER FREQUENCY OVERVOLTAGES AND ENERGY RATING

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Field tests were conducted at Toronto Cecil TS to determine the power frequency and surge voltages at the GIS/cable and oil feed pipe interfaces and the propagation characteristics of pipe-type cables. Measurements indicated that the polarizing cell loop inductance is about 89 μ H at low frequencies. Power frequency overvoltages of 1.8 kV and 120 V respectively across the GIS/cable and oil feed pipe interfaces were derived from measurements for a fault current of 30 kA. Models for calculating power frequency and surge voltages at the interfaces and transient energy dissipation in interface surge arresters have been developed.

1.0 INTRODUCTION

Insulated flanges are normally used at GIS/cable interfaces and at oil feed pipe interfaces of SF₆ substations to allow cathodic protection of high pressure oil-filled (HPOF) pipe-type cables. Without proper interface protection, transients generated by switching or system faults could cause the interface flange to break down resulting in a low impedance ionized path for the power frequency fault current to flow in preference to the more distant polarizing cell circuit. Then pipe burn-through is possible, leading to an oil leak, fire hazard and equipment damage. GIS/cable interface flange damage had occurred at London Talbot TS and Dofasco Bay Front TS in 1985 due to line-to-ground faults. Following these incidents, an HPOF Grounding Committee was established in 1986 to study the problem and recommend design changes to improve grounding of HPOF cables and surge protection of insulating flanges. As a result, several studies and laboratory tests were performed to determine the transient characteristics of GIS/cable interfaces and the grounding of pipe type cables to take into account high frequency surges due to a system fault. This included a preliminary calculation of surge voltages and 60 Hz temporary overvoltages stressing the interfaces due to fault current in the ground loop formed by the cable pipe, oil feed pipe and polarizing cell /1/.

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Polarizing cells installed at the oil pumping plant do not control fast transients generated by internal GIS faults or switching, mainly due to the relatively large loop inductance of the oil feed and riser pipes. The flange withstand strength could be increased, but the pipe coating can still cause insulation breakdown problems. Interface flange protection is normally achieved by bypassing surges using arresters. Protection using surge arresters needs to be coordinated with 60 Hz stress across the interfaces and transient energy dissipation due to fault current commutating to polarizing cells.

Based on these preliminary studies an interim surge protection scheme using Alsthom Cegelec PSI-A zinc oxide surge arresters has been provided for the GIS/cable interfaces at Cecil TS /2/. However, the thermal stress on these arresters needed to be determined. Also, the calculated overvoltages across the interface were based on several assumptions and needed to be validated to confirm the suitability of the arresters. Therefore, the committee reviewing the protection design identified a need for field measurements at Cecil TS. This project was requested and funded by Transmission Lines Design Department.

Tests were conducted at Cecil TS under simulated fault conditions on September 9 and 10, 1987. The objectives of the tests were:

- (a) To determine the 60 Hz and surge voltages stressing the GIS/cable interfaces and oil feed pipe flanges.
- (b) To estimate the transient energy dissipation in the interface protectors.
- (c) To determine the propagation characteristics of pipe type cables. These are used when simulating the surges entering the station due to system faults, switching or lightning.
- (d) To determine the ground potential rise and pipe cable shielding efficiency at 60 Hz to validate previously calculated values/3/.

Analysis of the test data is presently limited to the power frequency overvoltages, oil feed pipe protection and transient energy of the surge arresters at the GIS/cable interface. A detailed analysis of the frequency response measurements of the cable impedances will be done at a later date. A companion report (to be issued) describes the 60 Hz grounding system performance of the station.

2.0 TEST PROCEDURE

The 115-kV pipe-type cable circuit C7E between Cecil TS and Terauley TS was taken out of service for the tests. Details of the circuit are given in Figure 1. Working grounds were removed and access to the phases and the GIS/cable and oil feed pipe interfaces were obtained at Cecil TS end for either current injection or local grounding. Working grounds were either removed or installed on the three phases of the test circuit at the remote end for measurements. Existing surge protectors on the GIS/cable interfaces of the test circuit at Cecil TS were temporarily removed. The cathodic protection on the oil feed pipe was temporarily isolated at both ends leaving the cable pipe floating. For all other circuits at Cecil TS, cathodic protections were temporarily isolated and the oil feed pipes were directly grounded at both ends. The potential transformers on the test circuit at Cecil TS were temporarily disconnected. A patch panel expedited interfacing between the system and the Research instrumentation.

The following measurements were made at Cecil TS (refer to Figure 1 for definition of terms). The impedances were measured over a frequency range of 10 to 1010 kHz.

- (a) Polarizing cell loop impedance Z_L measured as V_P/I_R , with the phase conductors remotely grounded at Terauley TS and the oil feed pipe grounded at Cecil TS with the polarizing cell bypassed.
- (b) Oil feed pipe impedance Z_O measured as V_O/I_O .
- (c) Polarizing cell lead impedance Z_C measured as V_C/I_C with the polarizing cell bypassed.
- (d) Step response of surge voltages at the interfaces. Here, a step source of 6 V was applied between the R-phase of the test circuit and the ground and the voltages across the interfaces were recorded.

An HP3330B synthesizer and a two-channel HP3570A network analyzer were used to supply a sine wave test signal and to record the ratio of two inputs including phase angle. Here, the injected current and the split in the local ground were measured using two high frequency Pearson current transformers with an output of 1.0 V/A. The measured results were plotted on site by an X-Y plotter. The polarizing cell loop impedance was measured also at a lower frequency range up to 10 kHz using an HP3582A spectrum analyzer to supply the required current injection source and to record the ratio of the injected current to local voltage including phase angle. Here, the injected current was measured using a Ritz clip-on 5 VA, 150:5 A current transformer with 0.66 Ω shunt. For the time response tests, the surge voltages appearing at the GIS/cable and the oil feed pipe interfaces were only approximately measured using an oscilloscope without camera. A Nicolet digital recording system which gives greater accuracy than the oscilloscope had failed during the tests.

Safety precautions and procedures were observed and barrier controls were provided during the tests for personnel and equipment safety. Assistance was obtained from Central Regional staff in enforcing safety procedures, co-ordinating the tests, applying for the above outage, making temporary connections to the cable circuits and in conducting the tests.

3.0 MEASURED RESULTS

Figures 2, 3 and 4 give the measured impedances (both amplitude and phase angle) of the polarizing cell loop, oil feed pipe and polarizing cell lead respectively. The amplitude (Z) is plotted in log terms.

Table 1 lists the polarizing cell loop impedance measured using the spectrum analyzer over the lower frequency range up to 10 kHz.

TABLE 1
TORONTO CECIL TS
MEASURED POLARIZING CELL LOOP IMPEDANCE

Frequency (Hz)	Z_t (m Ω)
67	43/ <u>61</u>
100	56/ <u>64</u>
300	146/ <u>79</u>
1000	422/ <u>81</u>
3000	1269/ <u>85</u>
10000	4311/ <u>78</u>

3.1 Power Frequency Overvoltages at the Interfaces

At low frequencies, a polarizing cell loop inductance of about 89 μ H was estimated from the measured loop impedance of 43/61 m Ω at 67 Hz (Table 1). A loop impedance of 40/58 m Ω at 60 Hz was extrapolated from these measured results. For an ultimate fault current of 30 kA peak returning to Cecil TS due to a line-to-ground fault outside the station, this gives a power frequency voltage rise of about 1200 V peak across the GIS/cable interface without considering any dc offset. Assuming 100% dc offset (ie 30 kA), the voltage rise would be increased by about 600 V due to the resistive component of the loop impedance. Here, the dc resistance is assumed to be the same as the ac resistance.

Measurements (Figure 4) indicated that at lower frequencies, the polarizing cell connecting lead is mainly inductive with about 10 μ H. This results in a 60 Hz voltage rise of about 120 V peak across the oil feed pipe interface for the above fault current of 30 kA.

The measured voltages across the interfaces are given in Table 2 along with modelled values.

TABLE 2
TORONTO CECIL TS
POWER FREQUENCY OVERVOLTAGES ACROSS INTERFACES

Across	Measured (mV/A)	Modelled (mV/A)
GIS/Cable Flange	40/ <u>58</u>	* 55/ <u>66</u> - 30/ <u>83</u>
Oil Feed Pipe Flange	3.8/ <u>89</u>	4.8/ <u>70</u>

* Varies based on the permeability of the oil feed pipe material.

3.2 Surge Voltages

Accurate measurements of surge voltages appearing at the interfaces could not be made due to failure of instrumentation system, as mentioned earlier. With a step source of 6 V applied to the R-phase of the test circuit, voltages of about 100% and 50-100% were seen at the GIS/cable and oil feed pipe interfaces respectively as read from an oscilloscope display of the waveforms.

4.0 MODELLED RESULTS

4.1 Polarizing Cell Loop Impedance

The polarizing cell loop impedance for the test circuit was calculated based on a previously developed preliminary model/1/. The loop impedance consists of the self and mutual impedances of the conductors carrying the fault current and 100% of the fault current was assumed to return through the cable pipe due to the effective shielding of pipe-type cables. The formulas used in the calculations are given in Appendix A.

The polarizing cell loop for the test circuit (C7E) consists of about 50 m of stainless steel riser pipe, 40 m of magnetic (carbon) steel oil feed pipe, 4 m of cell connecting lead (127 mm² copper) and the ground grid conductors. The impedance of the polarizing cell itself is about 0.5 mΩ as per the manufacturer's data and was neglected. The impedance of the ground grid which consists of several short conductors in parallel combination was also neglected compared to the impedances of the oil feed and riser pipes. The loop impedance was calculated as the sum of the following:

- (a) Mutual impedance Z_1 of the riser pipe relative to phase conductor with equal current returning through the oil feed pipe (from equation 1 of Appendix A).
- (b) Self impedance Z_2 of the oil feed pipe which includes inductive reactance due to external flux with return current through the phase conductor (from equation 1 of Appendix A) and pipe internal self impedance (equation 2 of Appendix A).
- (c) Self impedance Z_3 of the polarizing cell lead which includes inductive reactance due to external flux with return current through the phase conductor (from equation 1 of Appendix A except that the conductor GMR is used instead of r_p) and the conductor ac resistance.

Assuming a separation of 2.5 m between the faulted phase and the oil feed pipe, the calculated impedances are given in Table 3. Two values for Z_2 are given in the table based on magnetic permeabilities of 1000×10^{-6} H/m (conservative value) and 10×10^{-6} H/m for the oil feed pipe respectively. The corresponding total loop impedances were calculated as 55.2/66 mΩ and 30.2/83 mΩ respectively. Thus, depending on the magnetic properties of the carbon steel which is greatly influenced by the carbon content, the modelled loop impedance could vary between the two values.

TABLE 3
TORONTO CECIL TS
MODELLED POLARIZING CELL LOOP IMPEDANCE AT 60 Hz

	Resistance (mΩ/m)	Inductance (μH/m)
Riser Pipe (Z_1)	-	0.76
Oil Feed Pipe (Z_2)	* 0.54 - 0.07	* 2.3 - 0.90
Polarizing Cell Lead (Z_3)	0.16	1.2

* Varies based on the permeability of the pipe material.

4.2 Power Frequency Overvoltages at the Interfaces

Power frequency overvoltages across the GIS/cable and oil feed pipe interfaces were calculated from the loop impedance and oil feed pipe grounding lead impedance respectively. Table 2 compares the modelled voltages with the measured values. Based on the conservative model, a voltage rise of about 1700 V peak across the GIS/cable interface was calculated for an ultimate fault current of 30 kA without taking into account any dc offset. Assuming 100% offset, the voltage rise would increase to about 2300 V peak due to the resistive component. The calculated voltage rise across the oil feed pipe interface would be about 140 V peak for the above fault current of 30 kA.

4.3 Oil Feed Pipe Interface Protection

Referring to Figure 1, the surge voltage across the oil feed pipe flange (V_o) was estimated from the surge voltage at the GIS/cable interface (V_p) by applying the voltage division rule assuming the wiring to be modelled by lumped inductances at high frequencies. For a time frame corresponding to 3-10 kHz range, the polarizing cell loop inductance and the cell connecting lead inductance are approximately 67 μH and 10 μH respectively as measured. Therefore, V_o would be about 15% of V_p which could be increased due to overshoot at the interface caused by losses and capacitance to ground.

With surge protection at the GIS/cable interface, the maximum value of V_p would be the peak operating voltage of the arresters. The transient voltage at the GIS/cable interface could reach about 4.5 kV with the existing three Cegelec surge arresters in series at the interface, assuming a peak operating voltage of about 1.5 kV for the arrester.

4.4 Transient Energy in Arresters Across GIS/Cable Interface

Total arrester energy was calculated as the product of the peak operating voltage of the arrester, the average surge current and the current duration. Appendix B describes how the arrester current and its duration could be estimated. For a line-to-ground fault on a HV circuit at Cecil TS, a peak surge current of about 30 kA would initially flow through the GIS/cable interface arresters, as estimated from a fault study by System Planning Department (Figure 5). A slope of about 67 kA/ms for the current through the polarizing cell was calculated (equation 1 of Appendix B) based on a peak operating voltage of about 4.5 kV for the three Cegelec arresters in series across the interface and a cell loop inductance of about 67 μ H (from measurements at 3-10 kHz). An arrester current duration of about 0.1 ms was estimated from this polarizing cell current and the fault current in Figure 5. The total energy dissipated in the existing Cegelec arresters across the GIS/cable interface was calculated as 7 kJ assuming a constant average arrester current of 15 kA and a peak operating voltage of 4.5 kV for the arresters. With the arresters at four locations around the interface, the energy in each series connection may be about 3 kJ (about 40% of the total energy) due to unbalance.

5.0 DISCUSSION OF RESULTS

- (1) The 60 Hz temporary overvoltages (TOV) stressing the GIS/cable interface were found to be about 1.8 kV as measured and 2.3 kV as calculated for a fault current of 30 kA. For duration of fault, interface protectors should be chosen such that the TOV is within their capability.
- (2) The measured polarizing cell grounding lead impedance of 3.8/89 m Ω at 60 Hz compares reasonably with the calculated value of 4.8/70 m Ω . The corresponding power frequency voltage rise of 120-140 V across the oil feed pipe flange for a fault current of 30 kA should be within the withstand strength of the flange.
- (3) An estimated surge voltage of more than 15% of the surge voltage at the GIS/cable interface was found to appear at the oil feed pipe interface (section 4.3). However, the model could not be validated due to lack of satisfactory field measurements. With surge protection at the GIS/cable interface, the surge voltages depend on the peak operating voltage of the surge arresters. An analysis of withstand capability of the flange and surge response of the interfaces and protective devices is required to determine the need for oil feed pipe protection and coordination.
- (4) The estimated energy dissipation of approximately 3 kJ in the three Cegelec arresters in series across the GIS/cable interface (section 5.3) exceeds the arrester rating of 1.5 kJ assuming that the Cegelec unit has a rating of 0.5 kJ per element. These results are only preliminary since the exact characteristics of the Cegelec arresters are not available.

6.0 CONCLUSIONS

1. A polarizing cell loop impedance of 43/61 m Ω at 67 Hz was measured at Cecil TS on the HV circuit C7E. The extrapolated loop impedance at 60 Hz is about 40/58 m Ω . This results in a power frequency overvoltage of about 1.8 kV across the GIS/cable interface for a fault current of 30 kA peak assuming 100% dc offset. The corresponding modelled value is about 2.3 kV based on conservative assumptions.
2. Measurements indicated that the cell connecting lead is mainly inductive at low frequencies with an inductance of about 10 μ H. The measured 60 Hz voltage rise across the oil feed pipe interface is about 120 V for the above fault current of 30 kA peak.

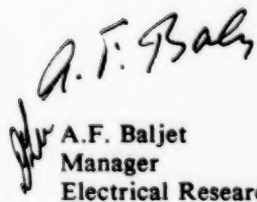
3. Power frequency overvoltages that would appear across both GIS/cable and oil feed pipe interfaces of SF6 substations can be calculated using the model described in this report.
4. A method for calculating transient energy dissipation in surge arresters across GIS/cable interfaces has been presented in this report. Based on this model, the total transient energy dissipated in the existing Cegelec arresters across the GIS/cable interface at Cecil TS would be about 7 kJ for a line-to-ground fault current of 30 kA peak, assuming a peak operating voltage of 4.5 kV for the three arresters in series.
5. Preliminary calculation indicated that more than 15% of the surge voltage at the GIS/cable interface would appear across the oil feed pipe flange at Cecil TS considering overshoot due to losses and capacitance to ground at the interface. With surge arresters at the GIS/cable interface, the maximum surge at the interface would approach the peak operating voltage of the arresters. The resulting stress at the oil feed pipe flange should determine the need for surge protection.

7.0 RECOMMENDATIONS

1. The model developed in this report for calculating energy dissipation in arresters and power frequency overvoltages at the interfaces could be used for selecting arrester ratings.
2. The existing Cegelec arresters at Cecil TS need to be replaced as the energy dissipation was found to exceed the thermal capability of the arresters according to the available data. New surge arresters with sufficient energy rating are currently under development at Research Division.
3. The surge voltages stressing the oil feed pipe flange should be compared with its withstand strength to determine the need for surge protection at the oil feed pipe flange.
4. Other options to achieve improved protection such as installing the polarizing cell close to GIS/cable interfaces to reduce temporary overvoltages across the interfaces and using insulated riser pipes to reduce pipe voltages should be further studied.
5. Further field tests would be useful to validate modelled surge voltages at the insulating flanges of SF6 stations, since measurements could not be done as planned in the recent tests at Cecil TS due to instrumentation failure.

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2. Memo dated January 19, 1987 to Mr. H.G. Jones, Stations and Transmission Programs from Mr. N. Fujimoto, Electrical Research.
3. P. Pillai, "Toronto Cecil TS - Grounding System Studies", Ontario Hydro Research Report No. 86-155-K, June 25, 1986.
4. E.P. Dick, "Strachan TS - Grounding System Calculations", Ontario Hydro Research Report No 83-433-K, November 7, 1983.

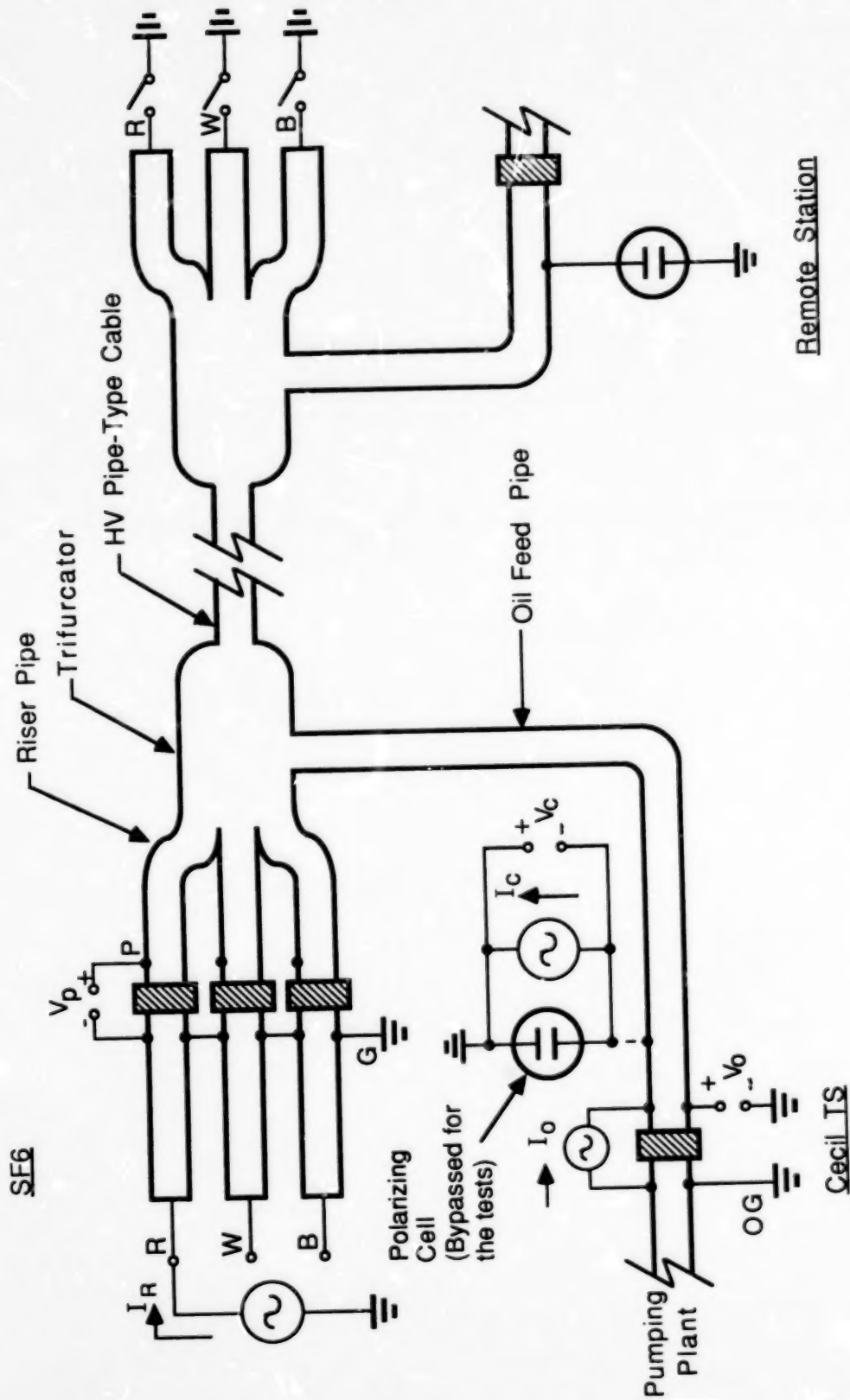


FIGURE 1
HV PIPE-TYPE CABLE CIRCUIT TESTS
TORONTO CECIL TS

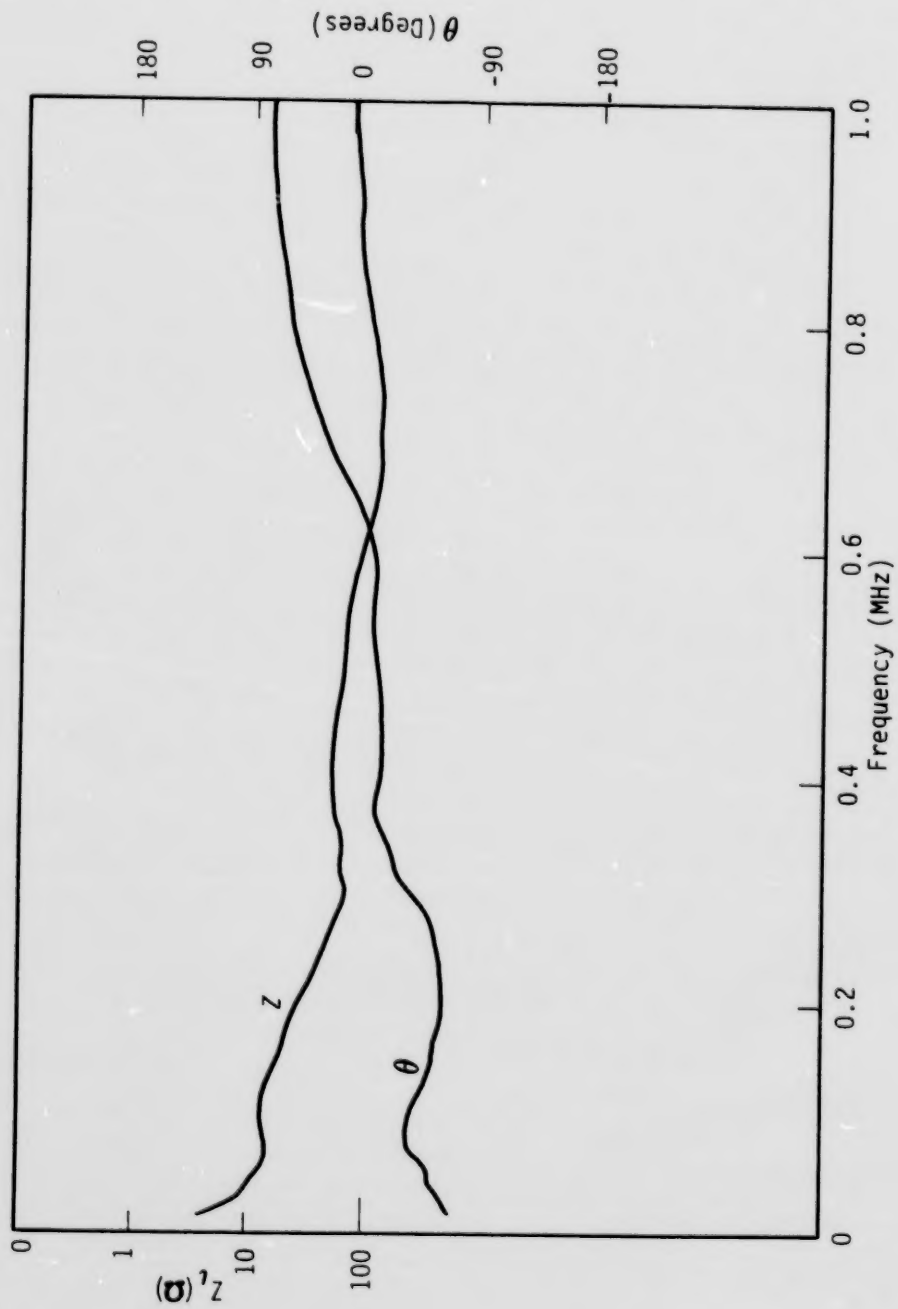


FIGURE 2
POLARIZING CELL LOOP IMPEDANCE, Z_L
TORONTO CECIL TS

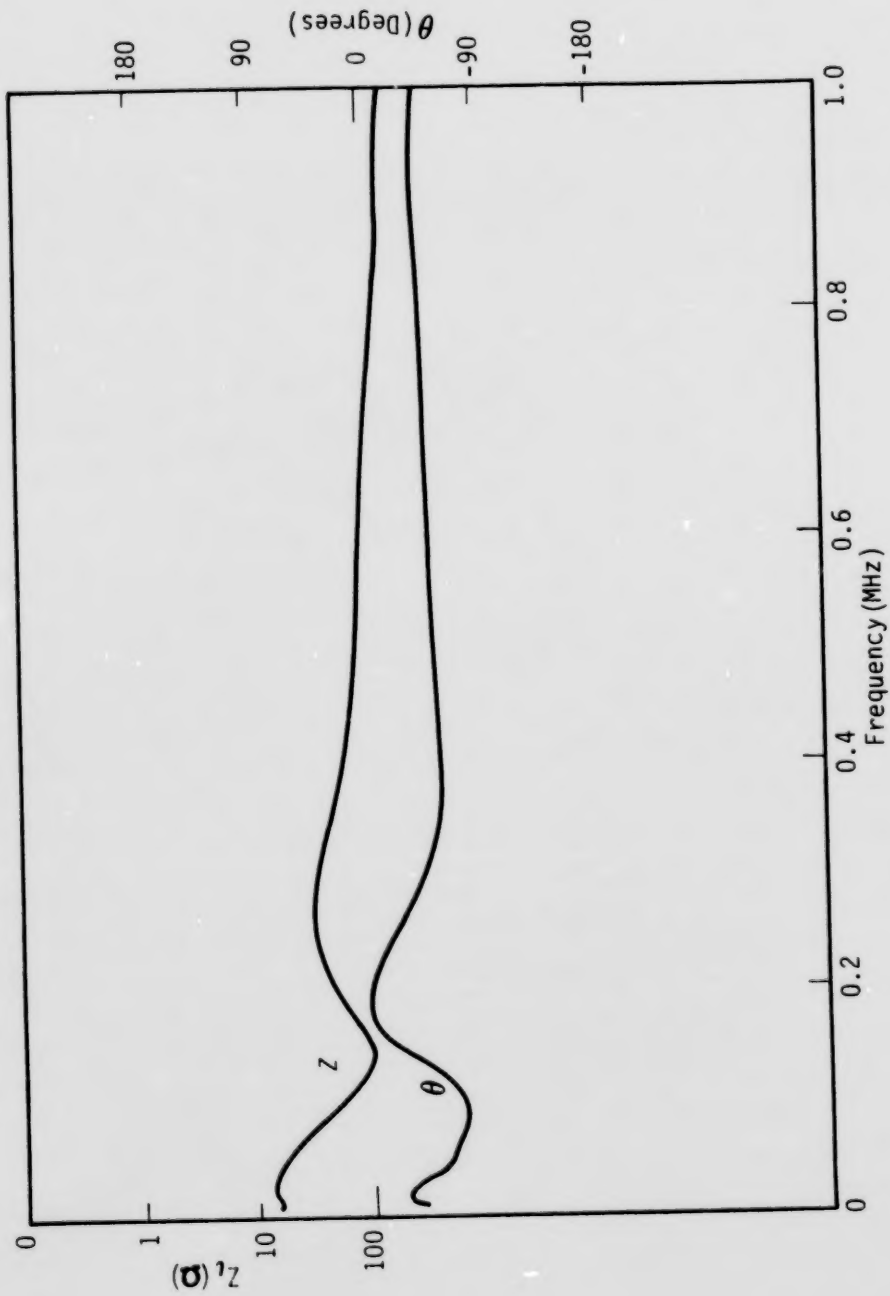


FIGURE 3
OIL FEED PIPE IMPEDANCE
TORONTO CECIL TS

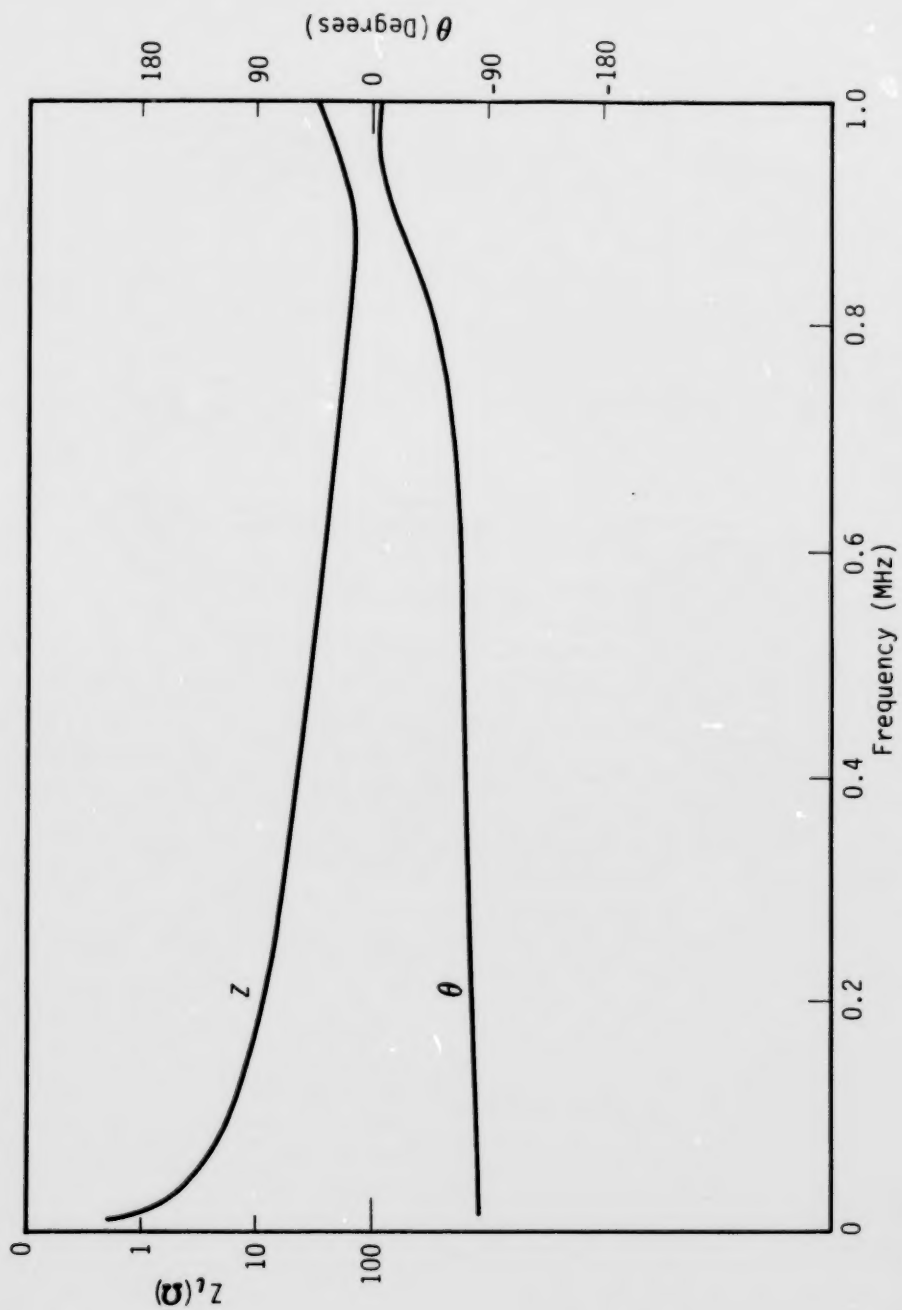


FIGURE 4
POLARIZING CELL LEAD IMPEDANCE
TORONTO CECIL TS

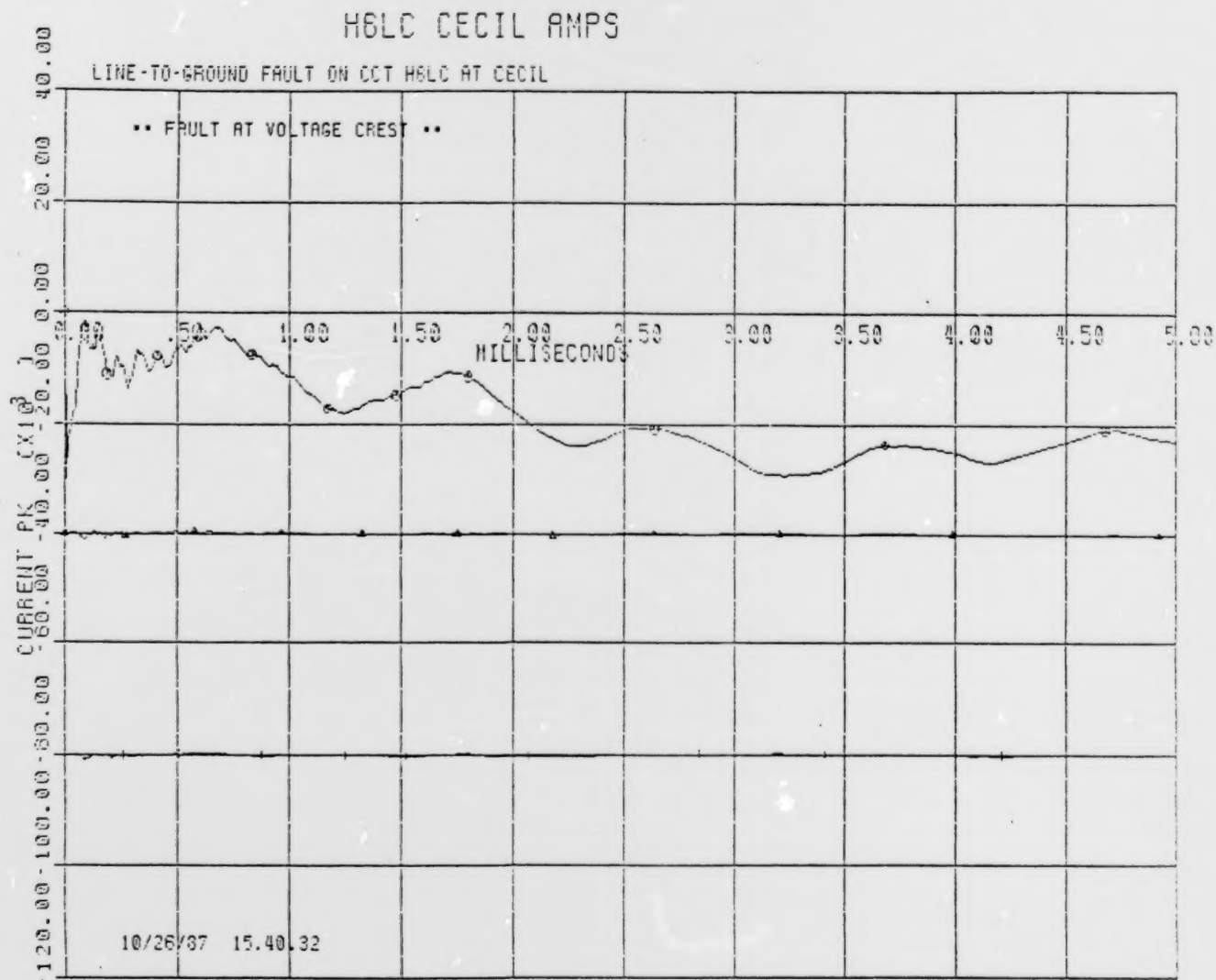


FIGURE 5
 LINE-TO-GROUND FAULT CURRENT
 TORONTO CECIL TS

APPENDIX A

FORMULAS USED IN CALCULATING POLARIZING CELL LOOP IMPEDANCE

Inductance of pipe due to external flux out to a distance of d (m) is given by:

$$L = \frac{\mu_o}{2\pi} \ln \left(\frac{d}{r_p} \right) \text{ H/m} \quad (1)$$

where, μ_o = permeability of air (H/m)
 r_p = radius of pipe (m)

Internal self impedance of pipe is given by:

$$Z_{ac} = R_{ac} + jX_{ac} \text{ (X/m)} \quad (2)$$

where, R_{ac} = ac resistance of pipe
 X_{ac} = pipe internal reactance

R_{ac} and X_{ac} can be estimated from the dc resistance of the pipe, R_{dc} and t/δ using Table III of /4/. Here,

$$R_{dc} = \frac{\rho}{2\pi r_p t} \text{ (}\Omega/\text{m)} \quad (3)$$

$$\text{Skin depth, } \delta = \sqrt{\frac{2\rho}{\omega \mu}} \text{ (m)} \quad (4)$$

where, ρ = resistivity of pipe material ($\Omega\cdot\text{m}$)
 r_p = pipe radius (m)
 t = wall thickness (m)
 ω = frequency (radians/s)
 μ = permeability of pipe

For $t/\delta < 0.2$, X_{ac} can be neglected and $R_{ac} = R_{dc}$

APPENDIX B

TRANSIENT FAULT CURRENT THROUGH GIS/CABLE INTERFACE ARRESTERS

For a ground fault on a HV cable circuit, the entire fault current i_f initially returns through the GIS/Cable interface arresters. Subsequently, the fault current is commutated over the polarizing cell at a rate given by:

$$\frac{di_c}{dt} = \frac{V_a}{L_c} \quad (\text{A/s}) \quad (1)$$

where, i_c = polarizing cell current (A)
 V_a = peak operating voltage of the interface arresters (V)
 L_c = polarizing cell loop inductance (H)

Then, the arrester current i_a is given by:

$$i_a = i_f - i_c \quad (2)$$

The duration of the arrester current is estimated when $i_f = i_c$ (ie $i_a = 0$), as shown in Figure C1 below.

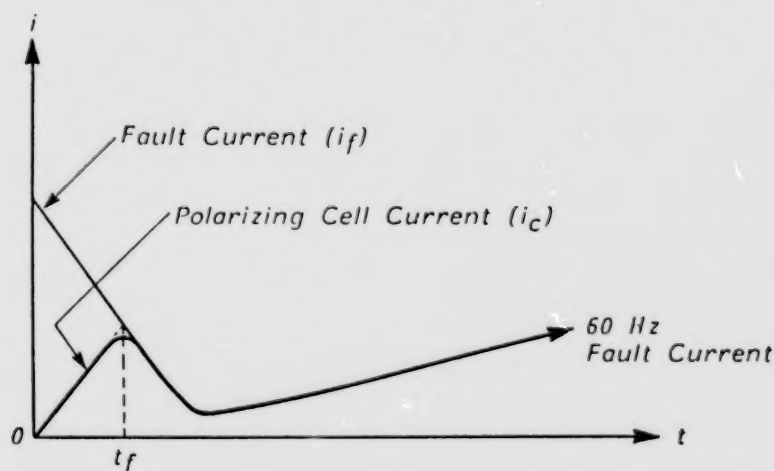


FIGURE C1
TRANSIENT FAULT CURRENTS